Incipient p-wave Superconductivity in a Si MOSFET

In a recent letter, Kravchenko and colleagues [1] reported a surprising insulator-metal transition (IMT) in a 2D high-mobility silicon metal-oxide-semiconductor field-effect transistor (MOSFET) as the electron density, n_s, increased from $8.14\times10^{10}/cm^2$ to $8.8\times10^{10}/cm^2$. Two key features that characterize the "IMT" are 1) the symmetry of the I-V curves around the I-V curve at the transition density, $n_c = 8.47\times10^{10}/cm^2$ and 2) the scaling of the resistivity as a function of electric field and temperature: $\rho(T,n_s) = f_1(|\delta_n|/T^b)$ with $b = 1/z\nu$ and $\rho(E,n_s) = f_2(|\delta_n|/E^a)$, $a = 1/[(z+1)\nu]$, $\delta_n = (n_s - n_c)/n_c$, $\nu = 1.5$ and $z \approx 0.8$. The fact that $z \approx 1$ signifies that electron correlations are dominant. Interpreted [1] as a true IMT, these experiments suggest that electron correlations thwart localization in 2D disordered systems. Theoretically, however, this question is still open.

We argue here that the observed "IMT" [1] is consistent instead with a transition from an insulator to a T=0 p-wave superconductor. Hence, the yet-unproven metallic state in 2D does not have to be invoked to explain the experimental data. Our argument consists of three parts. Consider first the I-V curves. In the insulator, the I-V curves indicate that a threshold voltage must be applied before current flows. This suggests that transport is activated in the insulator. Experimentally [2], the activation energy, Δ, was measured to vanish at the transition density [2]. In the conductor, the I-V curves exhibit negative curvature in the vicinity of zero applied voltage. This signifies a crossover to a state in which current flows in the absence of an applied voltage as in a superconductor. That this state of affairs obtains is simply a consequence of the symmetry between I and V on either side of the transition [3]. If I and V can be interchanged, then a charge activation gap in the insulator will manifest itself as a supercurrent on the conducting side. Naively, the magnitude of the supercurrent is proportional to the superconducting gap. We conjecture that $I \Leftrightarrow V$ symmetry might be related to the dual role played by the gap across the transition. At the transition density, the single particle localization length [4] is equal to the Cooper pair coherence length. While single electrons are localized by disorder, Cooper pairs at the brink of superconductivity can diffuse giving rise to a linear I-V characteristic [5]. Next, the electric field and temperature scaling of the resistivity given above is a natural consequence of the insulator-superconductor transition (IST) [6]. As a $T = 0$ transition, however, only superconducting phase or pair fluctuations will occur on the conducting side.

What about the pairing mechanism? At densities of $10^{11}/cm^2$, the electron interaction, $V_e \approx 10\epsilon_F$ [1]. Such strong correlations render standard BCS s-wave pairing mechanisms ineffective in driving the IST. However, at such low densities [7], we can expand the potential in powers of q/q_s for $q \approx 2p_F$ because $p_F q_s^{-1} \ll 1$. Here $q_s^{-1} = \lambda_s$ is a reciprocal screening length which for the 2D electron gas is of the order of the Bohr radius [7]. Consequently, $V_e(q=0) - V_e(2p_F) \approx 0$ and the s-wave component in the potential dominates. In this limit, Chubukov [8] showed for an arbitrary short-range repulsive interaction, $p_F a \ll 1$, where a is the scattering length, the dominant vertex renormalization of the scattering function $\Gamma(q)$ arises from third-order ladder exchange diagrams in the particle-particle channel. For $q \leq 2p_F$ such renormalizations lead to a p-wave interaction that is negative and as a consequence triplet ($S = \pm1$) p-wave superconductivity at T=0. A curious feature of the exchange mechanism is that it is destroyed predominantly by polarizing the spins in the intermediate scattering states. Hence, if the spins are polarized as in either a parallel or perpendicular magnetic field, the third-order vertex correction vanishes as should the p-wave pairing interaction. Recent experiments [9] indicate that the conducting state is indeed suppressed by either a parallel or a perpendicular magnetic field, consistent with a spin-polarization mechanism for the destruction of the superconducting state. Pairing fluctuations should vanish when the spin energy $g\mu_B H \approx \epsilon_F$; hence the characteristic field H_c should increase as a linear function of doping, δ_n. For $\epsilon_F = 0.6$mev, $H_c \approx 3T$. Experimentally, $H_c \approx 1T$ and increases with δ_n [9]. Further susceptibility and phase sensitive measurements are needed to confirm the p-wave scenario presented here.

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